Kalamazoo River PCBs:
Conceptual Site Model

June 27, 2005

Project Goals

- What are the relative contributions of the key PCB sources to PCB concentrations in fish?
- How will different remedial alternatives affect future fish PCB levels?
- CSM is the first phase
  - Qualitative description of the processes that link PCB sources with risk-based targets
    - Targets: Fish, sediments and water
    - Sources: sediments, banks, groundwater, floodplains, external sources
  - Limited quantification of sources (not constrained by mass balance)
  - Characterization of natural recovery

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Map

- Channel – blue
  - Tribs, too
- Floodplain – green
- Dams
- Key locations: M89, Comstock, Portage Creek

Site Background

- Watershed over 2,000 sq mi
  - Mostly forest and agriculture
  - Residential, commercial and industrial along the river

- 50 miles of river from Morrow Lake Dam to Lake Allegan Dam
  - Seven dams

- High-gradient free-flowing reaches with coarse-grain bottom and impounded reaches behind dams with fine-grain sediments
  - Average flow 1,100 cfs at Comstock
  - Flow increases 60% from Comstock to Lake Allegan Dam
  - Slope ~ 2 ft/mile
  - Average width ~200 feet, wider in impoundments
  - Average depth ~ 4 ft
  - Travel time about 2 days under low flow conditions

- Floodplains extensive in some reaches
  - heavily vegetated
  - Contaminated with PCBs

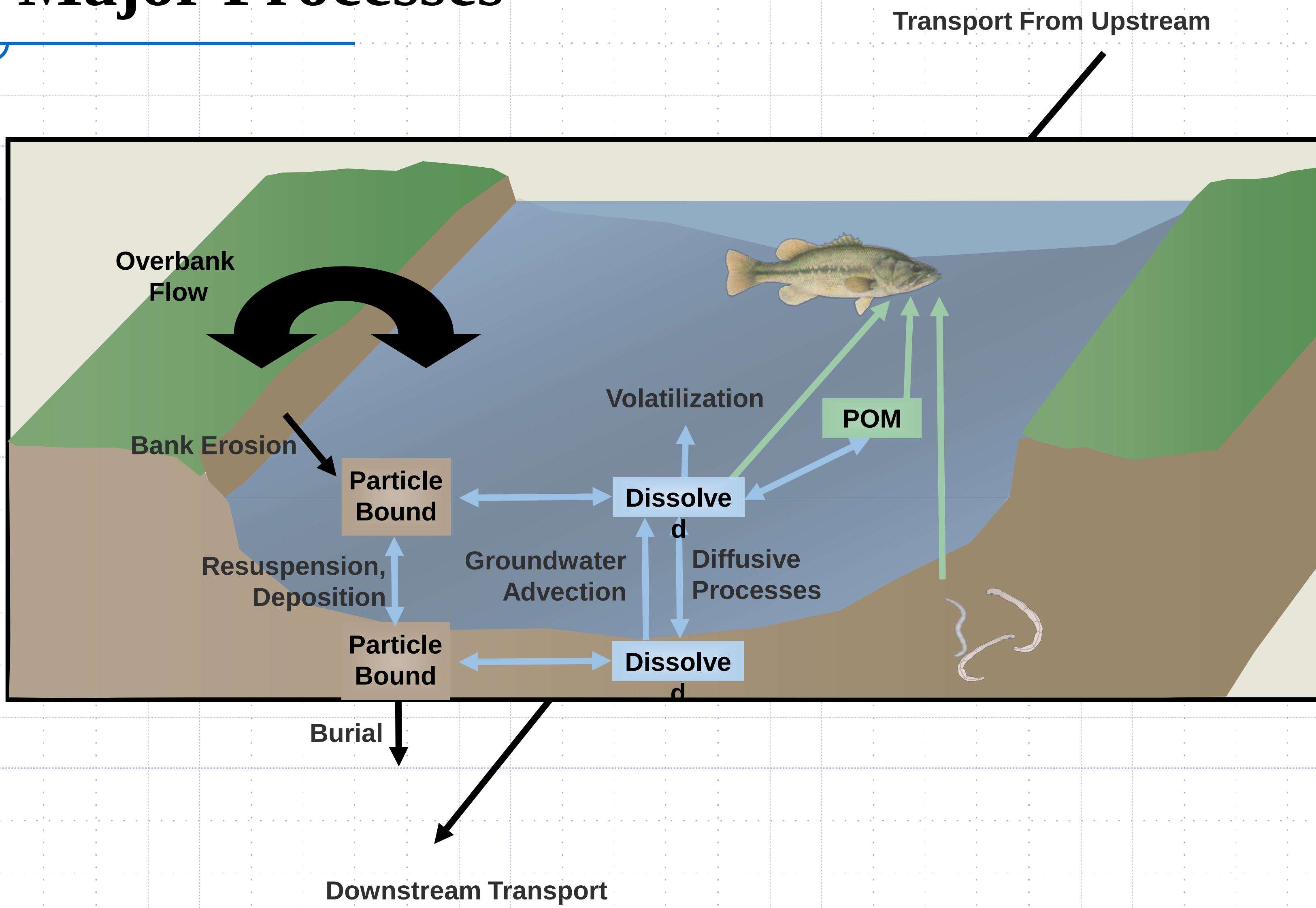
- Overhanging, eroding banks are present

- Multiple PCB sources along river
  - Most of the PCBs in the river are Aroclor 1242; other Aroclor(s) present as well

Site Background

- PCB use stopped in 1971
- Ongoing loading from upstream of the study area, and possibly from contaminated floodplains and landfills
- Plainwell, Otsego and Trowbridge dams drawn down in early 1970s
  - Channels incised into floodplain
  - Heads of 5 to 10 feet remain

Major Processes



Complete this

Sources of Information

- PCB measurements in sediments, water and fish
  - KRSG and MDEQ
  - Series of studies in early 1990s and 1999-2004
    - Mass balance based upon annual biweekly survey in 2000-2001
  - Low-flow and high-flow studies

- Studies of individual processes
  - Bank erosion
    - Pin study, PCB surveys in floodplains
  - Floodplain inundation
    - MDEQ SPMD study in Trowbridge Impoundment
  - Sediments resuspension
    - Sedflume studies
  - Groundwater
    - River flow data, limited well data, drainage area estimation

Contents

- Hydrodynamics, sediment transport and bank erosion

- PCB fate, transport and bioaccumulation
  - PCBs in water
    - Low-flow conditions
      - Groundwater contribution
    - High-flow conditions
      - Bank erosion contribution
      - Floodplain inundation
  - PCBs in sediments
  - PCBs in fish
  - Natural recovery

Hydrodynamics, Sediment Transport and Bank Erosion

CSM Summary: Hydrology & Hydrodynamics

- Overbank flow typically occurs when discharge exceeds ~1.5-year flood level
  - Most extensive floodplain inundation occurs in Otsego City and Trowbridge reaches

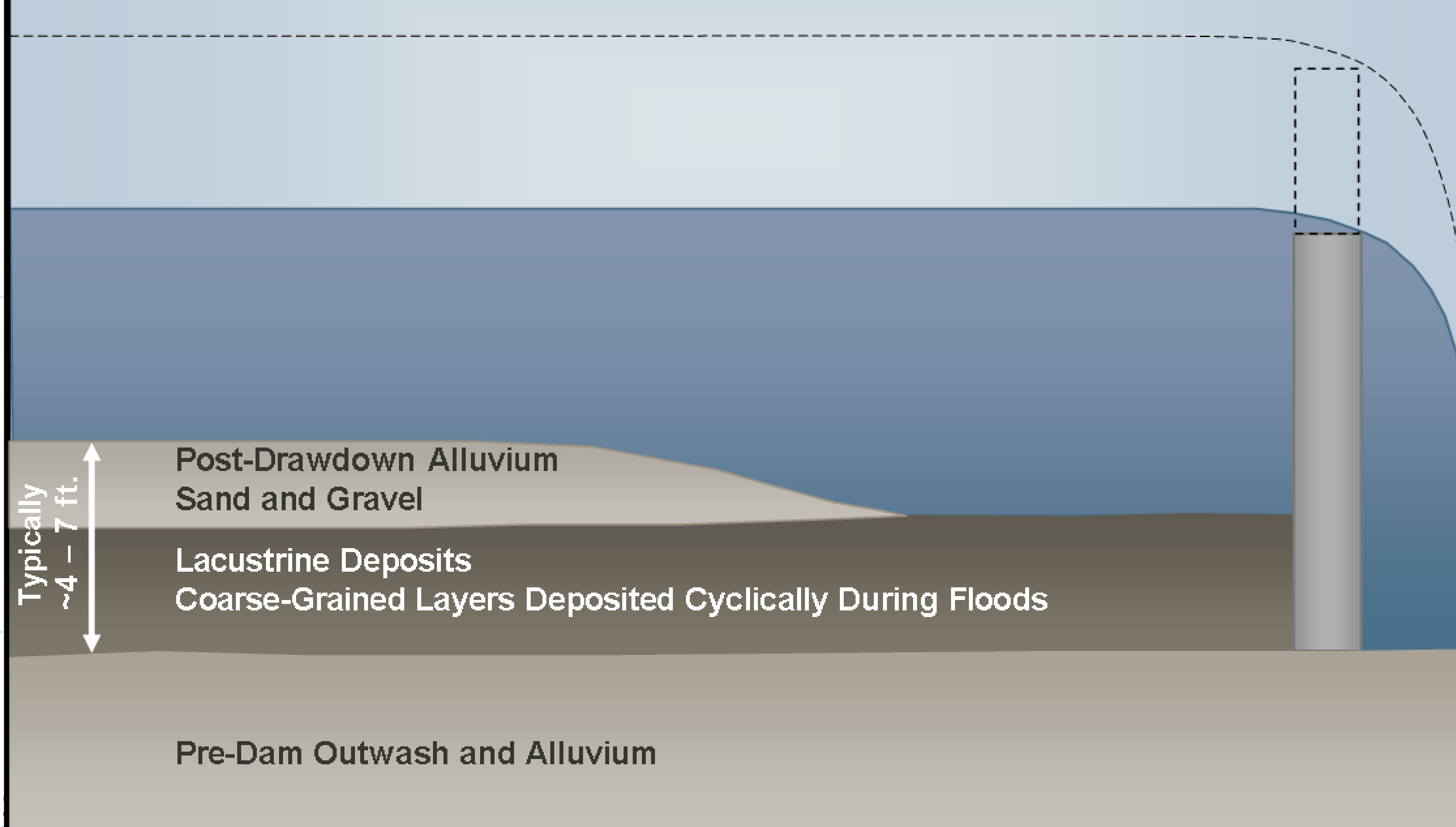
- Groundwater flow tends to be a minor component of the overall flow balance in the Plainwell, Otsego City, Otsego and Trowbridge reaches
  - Groundwater gain across reaches is about X% of river discharge

Impoundment Bed Structure

Before Dam Drawdown

Impoundment Bed Structure

After Dam Drawdown



Probable Impact of Future Dam Removal

- Pre-dam river channel
  - Relatively high gradient
  - Primarily composed of sand and gravel

- Removing a dam will increase hydraulic gradient in present backwater region upstream of dam

- Increased hydraulic gradient will cause bed erosion
  - Channel will tend to return to pre-dam conditions
  - Rate of bed degradation is uncertain

CSM Summary: Geomorphology & Bed Structure

- Between Morrow and Trowbridge Dams, pre-dam (i.e., ‘natural’) condition of river is, generally, a sand-gravel channel with relatively high gradient

- Dam removal, past and future, causes:
  - Erosion of cohesive sediments deposited in dam backwaters
  - Transformation of surface layer composition from cohesive to non-cohesive as channel reverts to pre-dam conditions

CSM Summary: Sediment Transport

- Results of the 2000-2001 sediment mass balance indicate that the sediment bed was:
  - Net erosional from Morrow Dam to Otsego City Dam
  - Net depositional from Otsego City Dam to Trowbridge Dam
- Sediment loads from upstream and tributary sources are underestimated at the present time
- Primary composition of suspended sediment load is clay/silt
- Bed load is typically a minor component of the total sediment load

CSM Summary: Bank Erosion

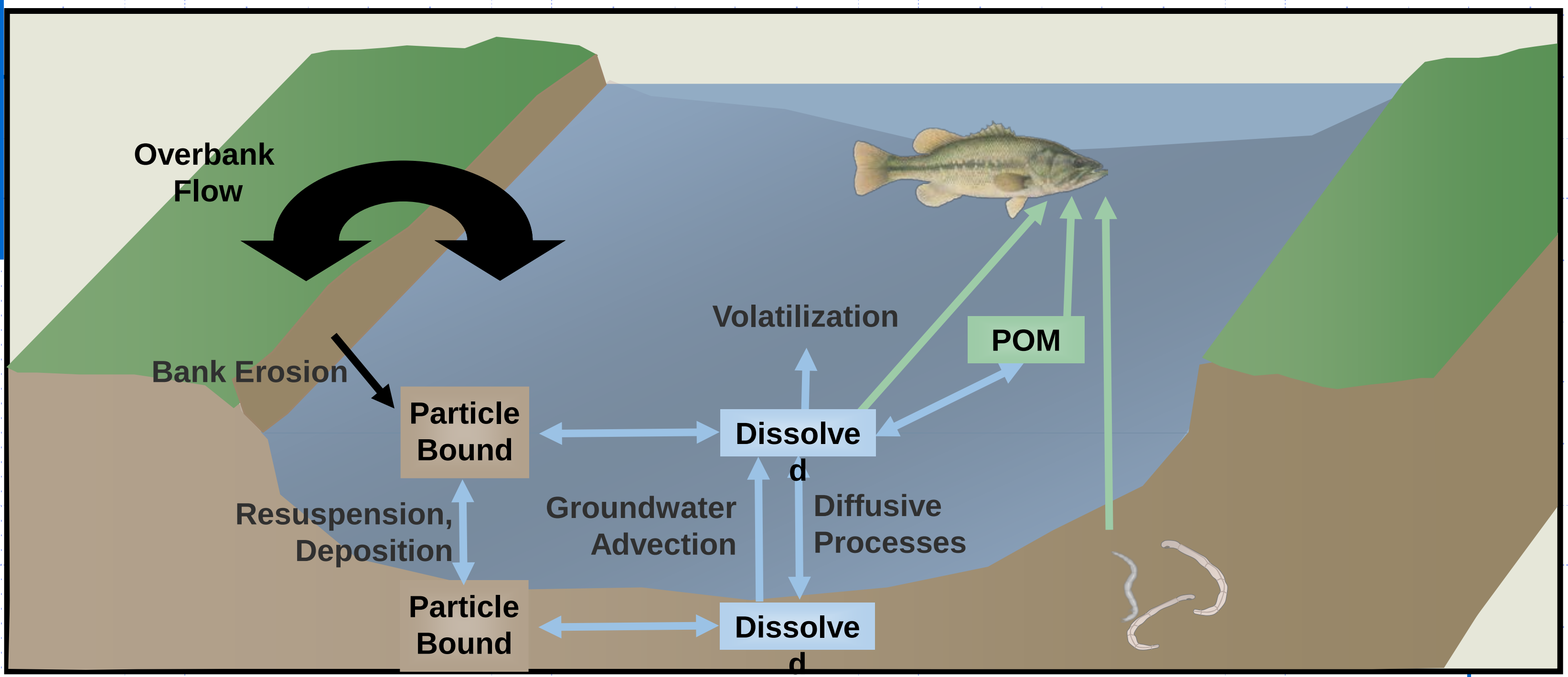
- Minor lateral migration of the river channel has occurred between Morrow and Trowbridge dams during the last 100-150 years

- Bank erosion loads in Plainwell and Otsego reaches are similar
  - ~500 – 1,000 MT/yr

- Bank erosion load in Trowbridge reach is higher than Plainwell and Otsego reaches
  - ~2,500 MT/yr

- On annual timescales, sediment loads due to bank erosion are at least 5-10 times smaller than suspended sediment load

PCB Fate, Transport & Bioaccumulation



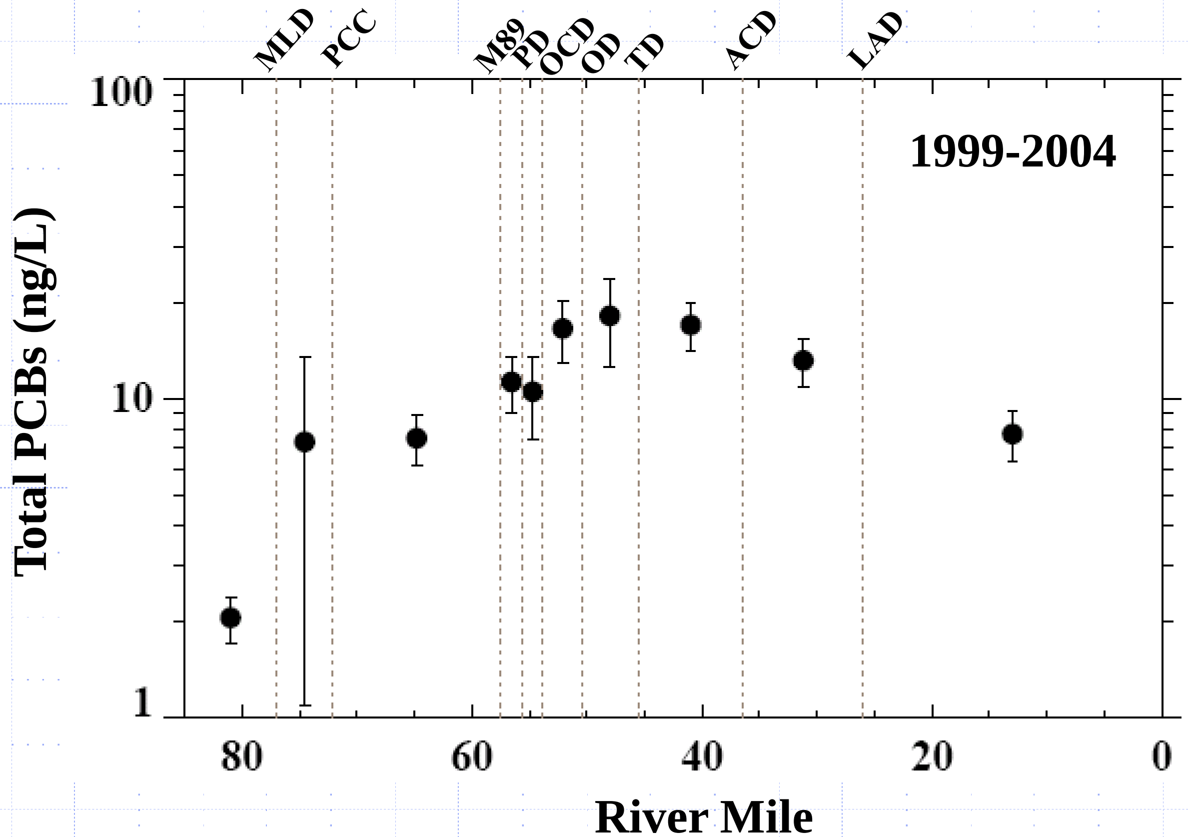
Total PCBs in Surface Waters

- Issue: How do PCB concentrations change with location in the river? Do gradients indicate likely sources?

- Approach: Distinguish low-flow from high-flow conditions
  - Different mechanisms controlling PCB concentrations

- Analysis
  - Flow at Comstock <2,500 cfs
  - Data collected by KRSG and MDEQ
  - 1999-2003

Total PCBs in Surface Waters: Low Flow



PCB concentrations increase down to Trowbridge Dam.
This indicates distributed source(s) within river.
Decrease downstream of Trowbridge is due to dilution & deposition.

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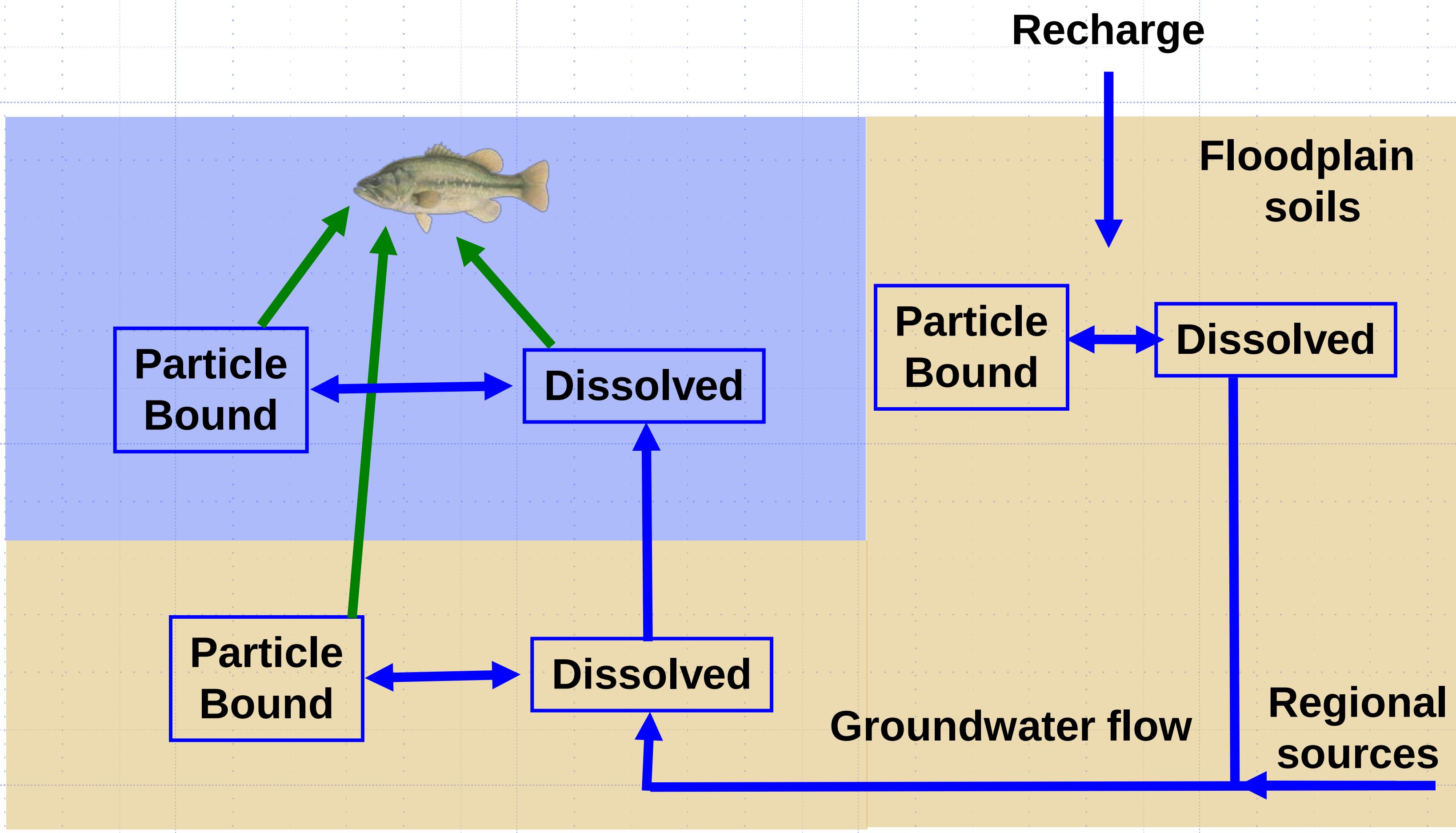
CSM Summary: Water Column, Low Flow

- PCB levels increase from Comstock to Trowbridge
  - Indicates in-stream source(s)
- Within each impoundment, PCB contamination in water is derived:
  - partly from local sourcees (sediments and banks)
  - partly from upstream
- Sediment bed source
  - Source strength greater during warmer months than during colder months, suggesting biological component

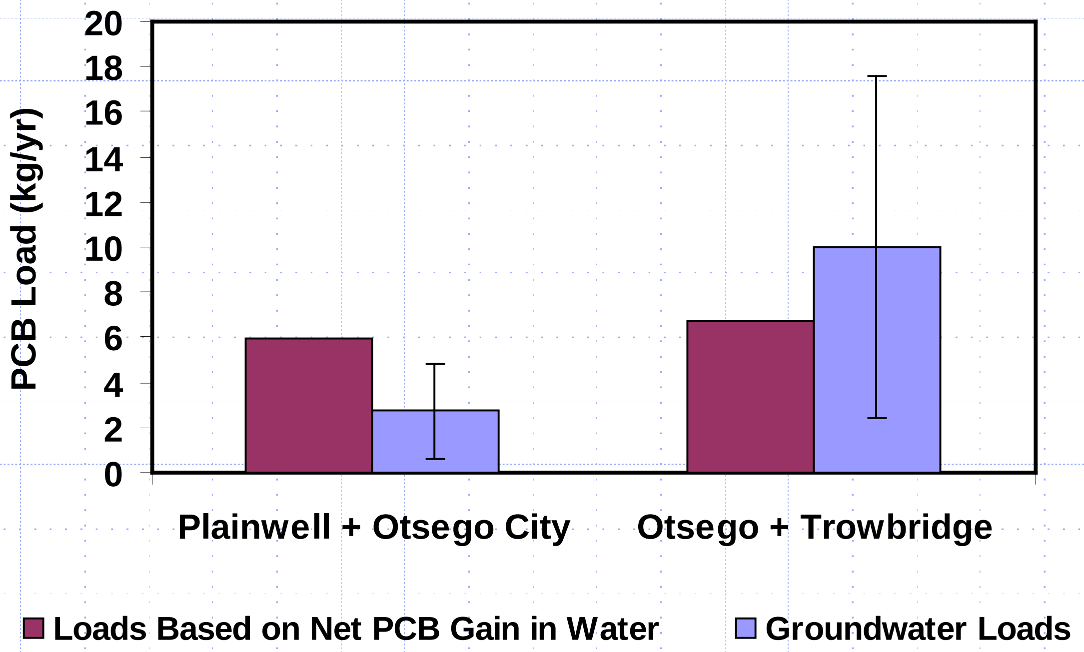
Groundwater



Groundwater Contribution

- **Issue: To what extent does groundwater contribute to the change in PCB concentration with distance downstream?**
- **Approach: Compare PCB load gain in the water with independently-estimated groundwater PCB load**
- **Analysis**
  - **Load gain in the water**
    - **2000/2001 KRSG biweekly sampling: annual average load under low-flow conditions**
  - **Groundwater load**
    - **Mechanism: As groundwater percolates through the sediment bed, PCBs sorb or desorb from particles in the bed, and the water takes on the PCB concentrations of pore water**
    - **Flows based upon direct drainage and Darcy's law**
    - **Pore water PCB concentrations computed based upon**
      - **Average carbon-normalized surface sediment PCB concentrations in each reach (1999-2003, 0-6")**
      - **Average partition coefficient computed using congener-based sediment data for entire study area (KRSG; n=95)**

Groundwater Contribution



Error bars indicate estimates based upon groundwater flows computed by direct drainage by Darcy's law

Groundwater may be a significant mechanism for the transport of PCBs from the sediments to the water column.

DG\\Mass balance.xls, Groundwater

CSM Summary: Groundwater

- Contribution continuous
- Concentrations likely reflect pore water
  - As groundwater percolates upwards through the sediment bed, PCBs sorb/desorb from the bed particles
- Groundwater contributes dissolved-phase PCBs
  - Most of this material will likely be transported downstream
- This is one of several mechanisms underlying low-flow flux of PCBs from the sediment to the water column
- Groundwater is potentially a significant vector for PCB transfer from sediments to water under low-flow conditions

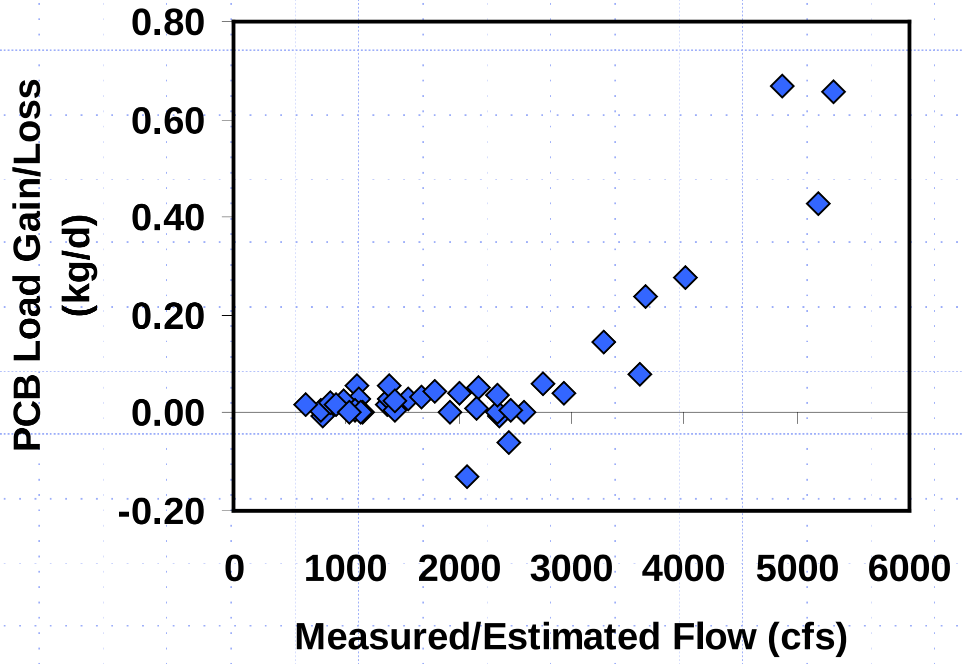
Total PCBs in Surface Waters – High-Flow Conditions

- **Issue: What mechanisms control PCB concentrations under high-flow conditions?**

- **Approach: Explore relationship between PCB load gain, TSS load gain and flow**

- **Analysis**
  - **Evaluate PCB and TSS data matched with estimated flows over a one-year period**
  - **Data collected by KRSG**
  - **2000-2001**
  - **Biweekly sampling + storm sampling**
  - **One reach presented here: Plainwell + Otsego City impoundments**

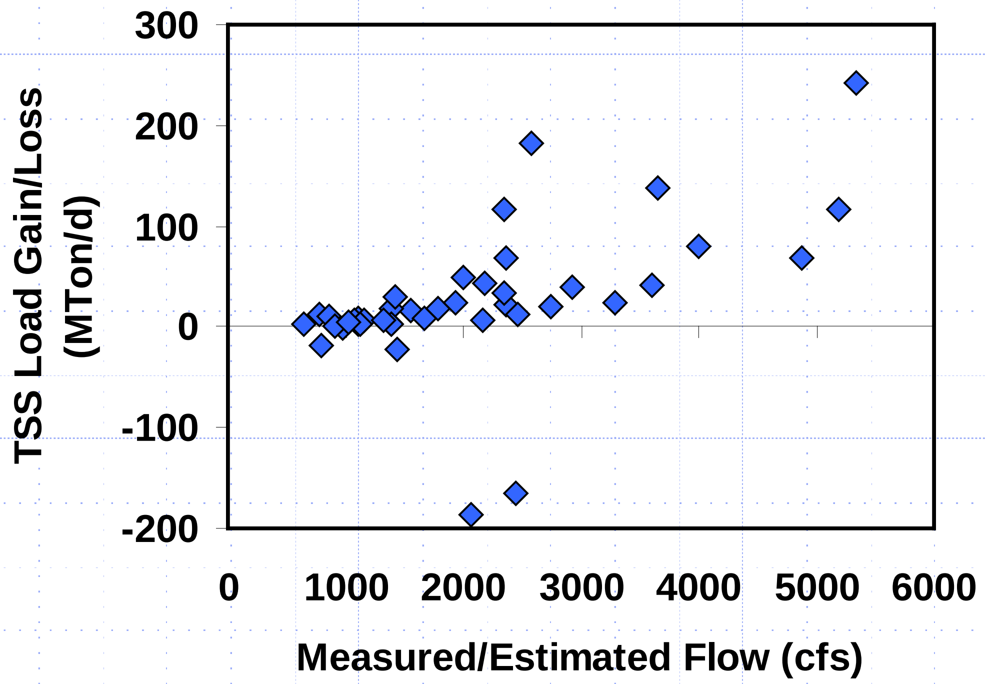
PCBs Load Gain vs. Flow



M-89 in Plainwell (KM-4) to Farmer St (KM-5)

PCB loads increase with flows > 2,500 cfs, indicating a change in mechanism

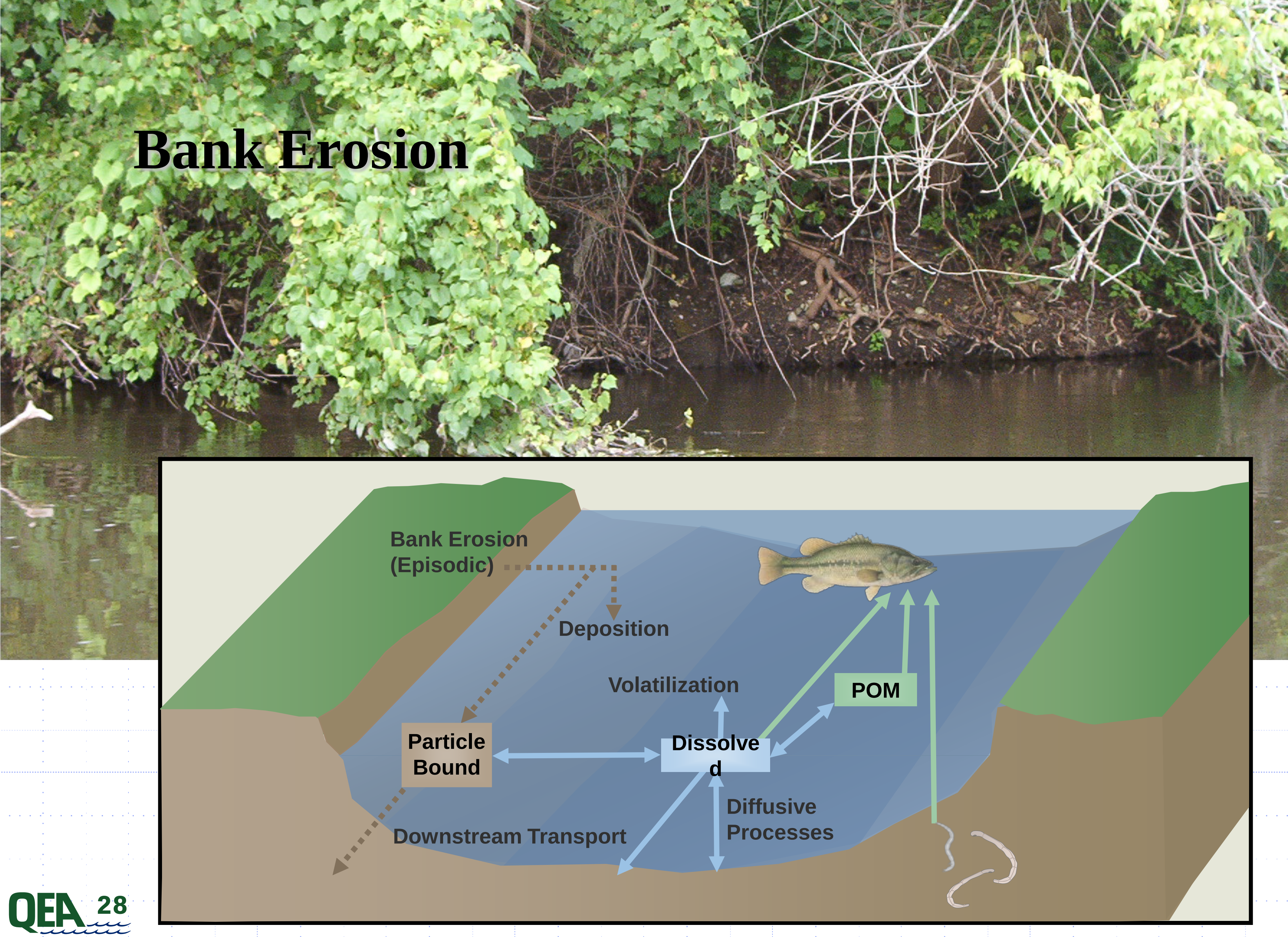
TSS Load Gain vs. Flow



M-89 in Plainwell (KM-4) to Farmer St (KM-5)

TSS loads increase with flow.
This suggests PCB load increase is due to resuspension or bank erosion.

Bank Erosion



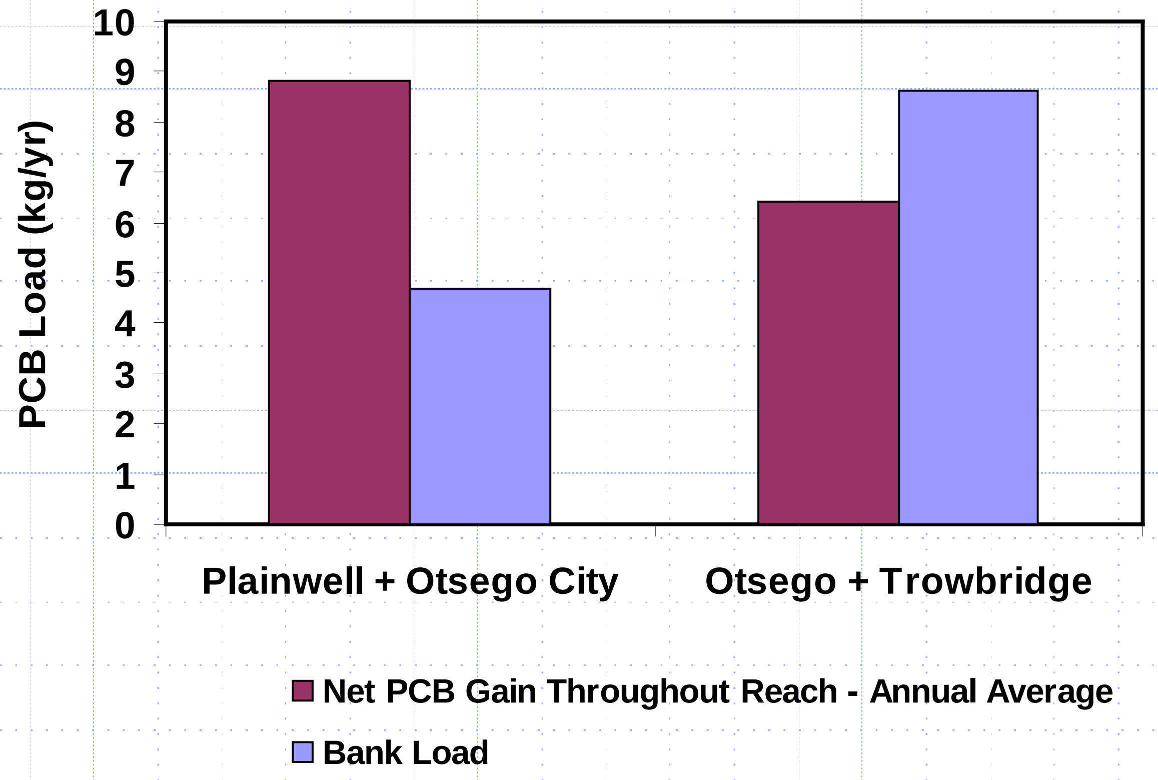
Bank Erosion

- Issue: To what extent does bank erosion contribute to PCB contamination in the river?

- Approach: Compare PCB load gains in the water with independently-estimated bank erosion loads

- Analysis
  - PCB load gains
    - Compute using PCB data matched with estimated flows
    - Data collected by KRSG
    - Annual average: all data collected 2000/2001
    - High-flow: during the April 2000 and February 2001 storms
  - Bank erosion
    - Estimate of mass of sediments eroded per foot of bank based upon pin study (LTI estimate)
    - Length of river bank subject to erosion: dam to head of backwater; use proportion of bank observed subject to erosion during the pin study
    - PCB concentrations in banks: average of data collected within 17 feet of the river edge, 1999-2003, to 24 inch depth
      - Plainwell: n=93; Otsego: n=9; Trowbridge: n=8
      - Duplicates averaged and non-detects set = ½ DL

Bank erosion – PCB Loads



PCBs released from banks could be sufficient to account for a large fraction of the load increase across the reaches, on an annual average basis

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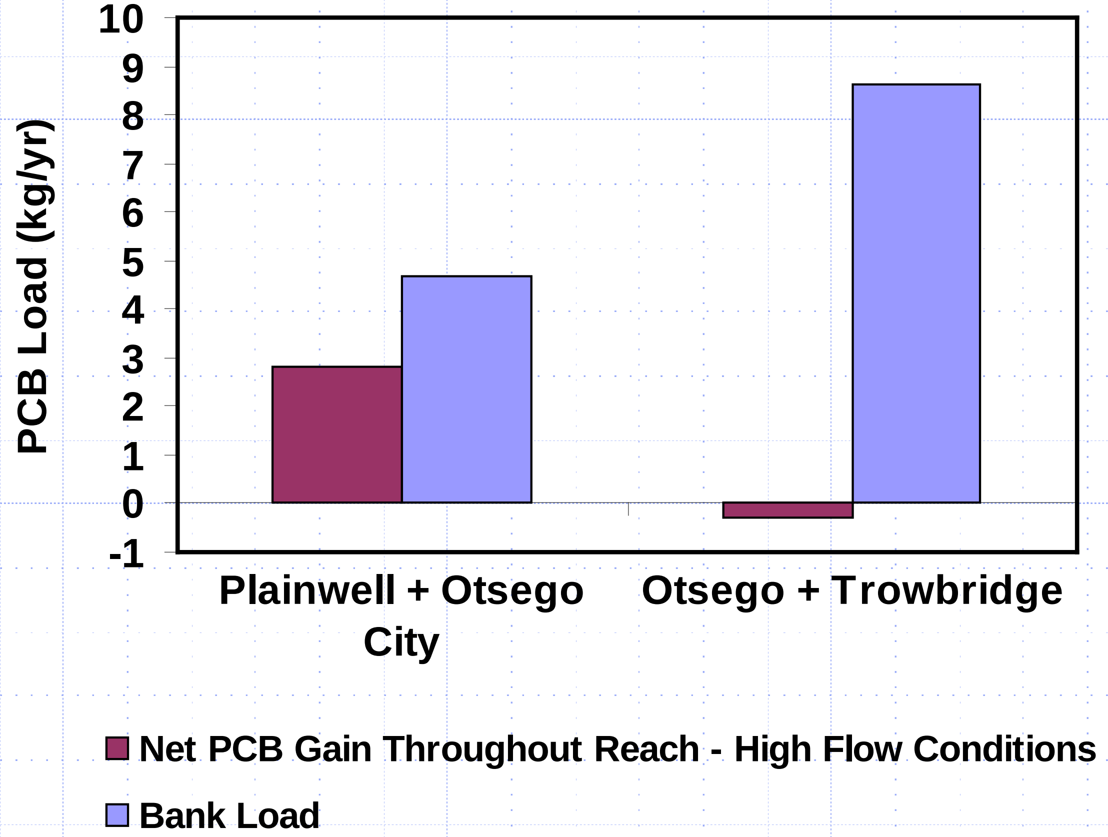
Bank erosion – PCB Loads – High-Flow Conditions



PCBs released from banks appear to be more than sufficient to account for the load increase during high flow periods.
Therefore, at least some of the bank material may settle within the reach.

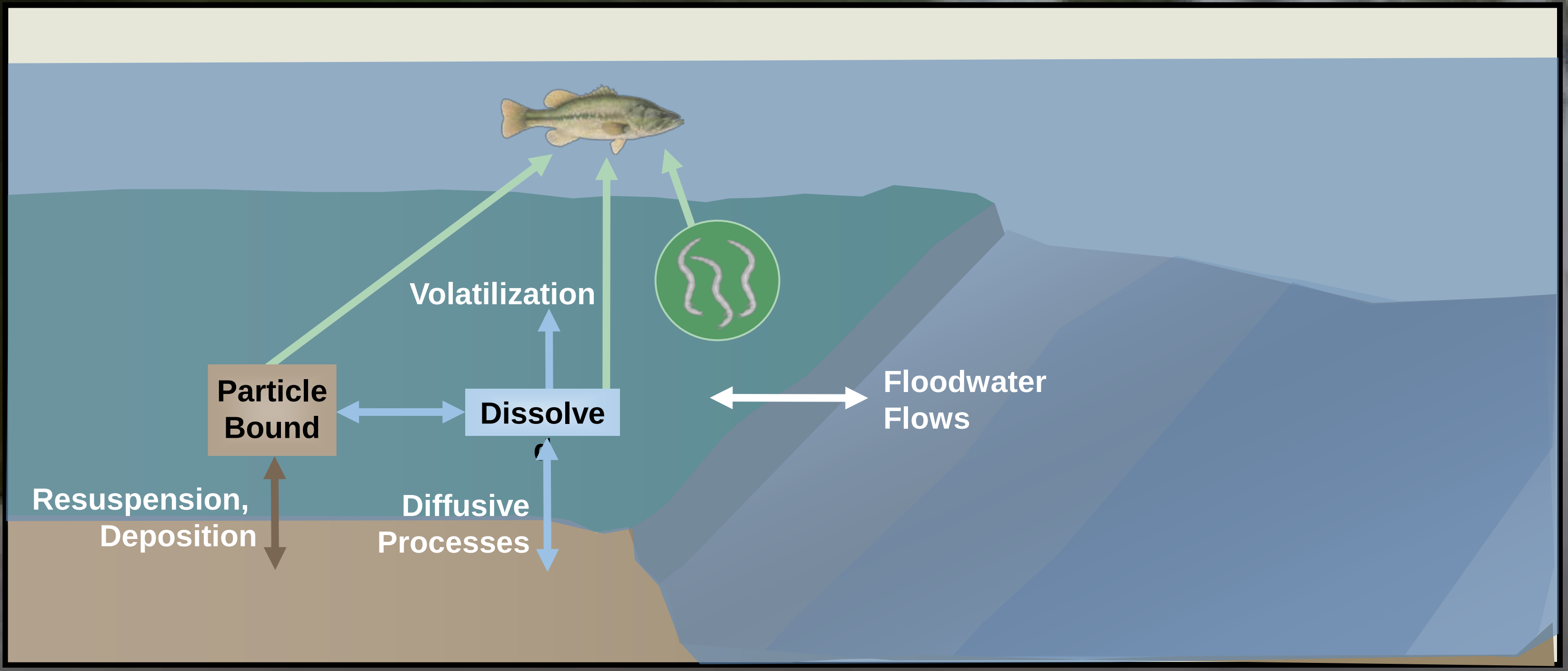
DG\\Mass balance.xls

CSM Summary: Bank Erosion

- Banks contribute particle-bound PCBs
  - Some of this material will settle within the same reach
    - This material may be buried, may diffuse back into the water column, or may be consumed by benthic invertebrates
  - Some fine material will be transported downstream
  - PCBs will desorb, and dissolved PCBs will be transported or volatilized
  - Contribution episodic

- Banks are likely to be a significant source to the sediments
  - PCB concentrations higher than sediments
  - This is likely to impact the rate of natural recovery

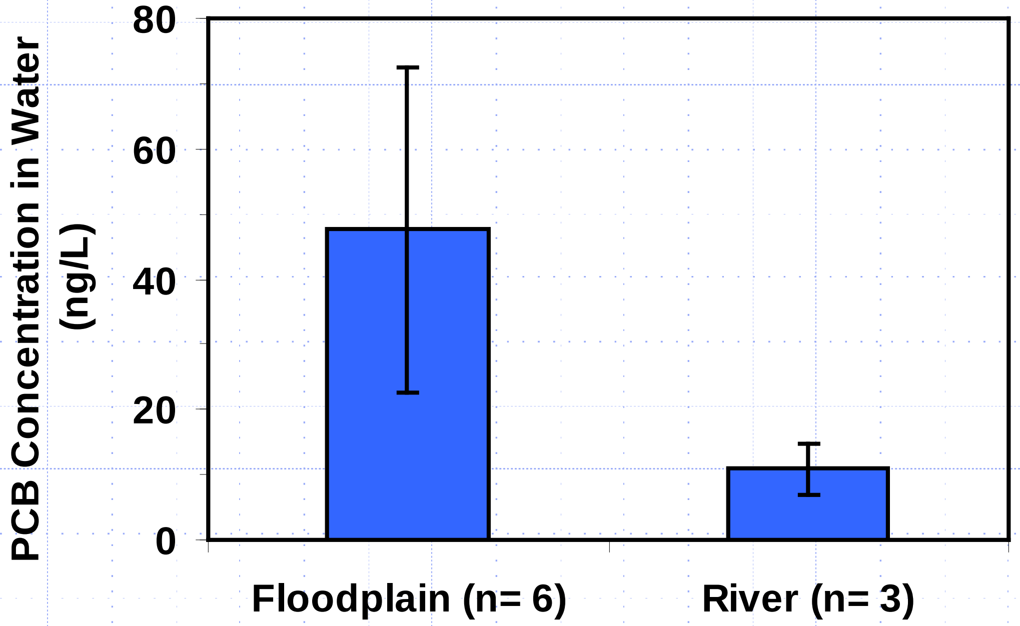
Floodplain Inundation



Floodplain Inundation

- Issue: Are floodplains a source of PCBs to the waters of the river during inundation?
- Approach: Compare PCB concentrations in floodwaters and in the river channel
- Analysis
  - MDEQ study, including SPMD deployment and water column measurements
  - Trowbridge Impoundment

PCBs in Floodplain Waters During Inundation



Mean +/- 2SE
Source: MDEQ

PCB levels in water were found to be elevated in the inundated floodplain, relative to the river channel.
This suggests that PCBs flux from the floodplain to the water.

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CSM Summary: Floodplain Inundation

- Relatively frequent and can be long-lasting

- There is evidence for floodplain PCB source

- Impact of this source depends on:
  - Duration of inundation
  - Extent of inundation
  - Extent to which fish move onto the inundated floodplain
  - Exchange flows between inundated floodplain and river channel

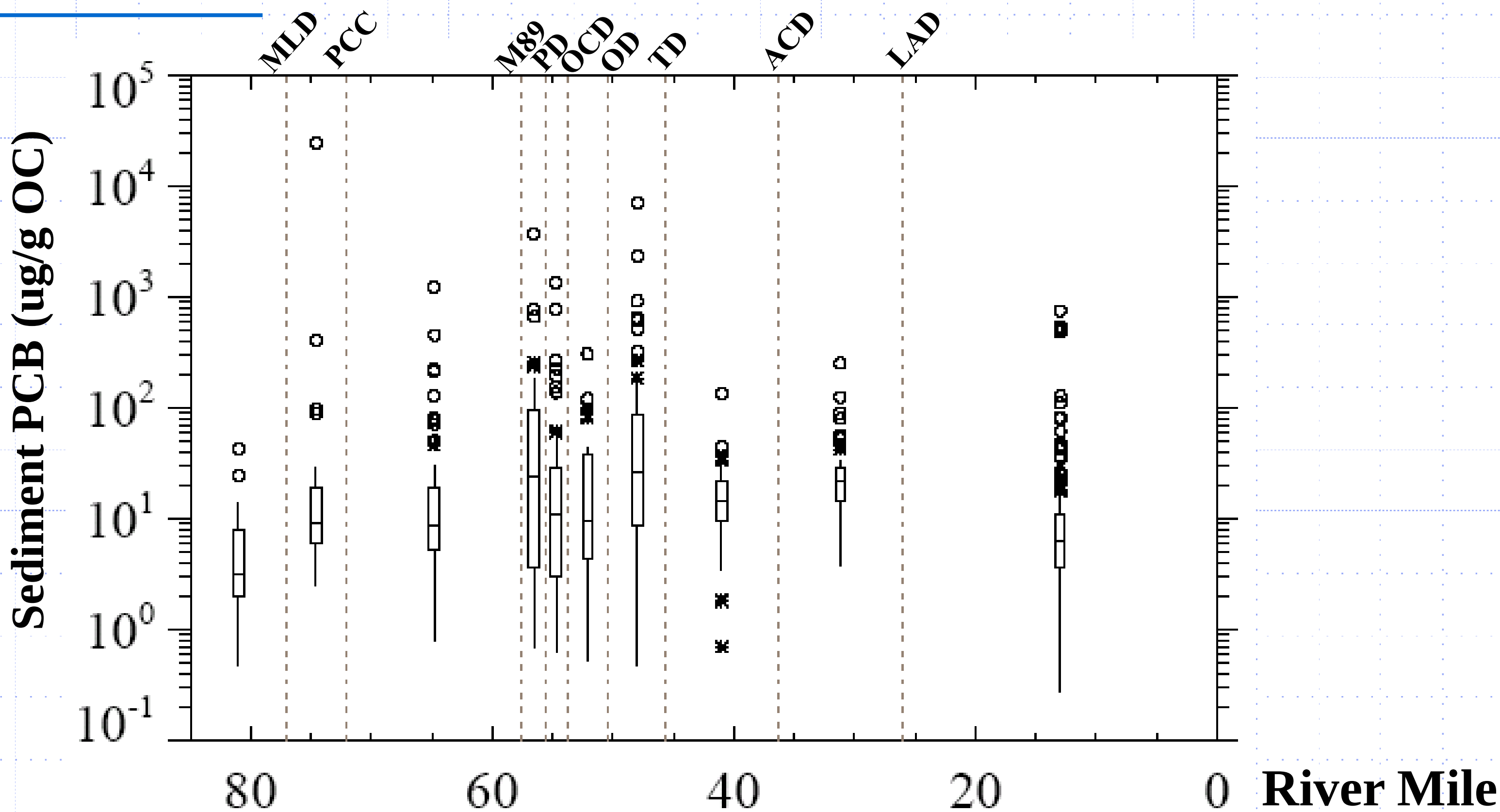
PCBs in Surface Sediments

- **Issue: How do PCB concentrations change with location in the river? Do gradients indicate likely sources?**

- **Approach: Parametric and non-parametric evaluation of gradients**

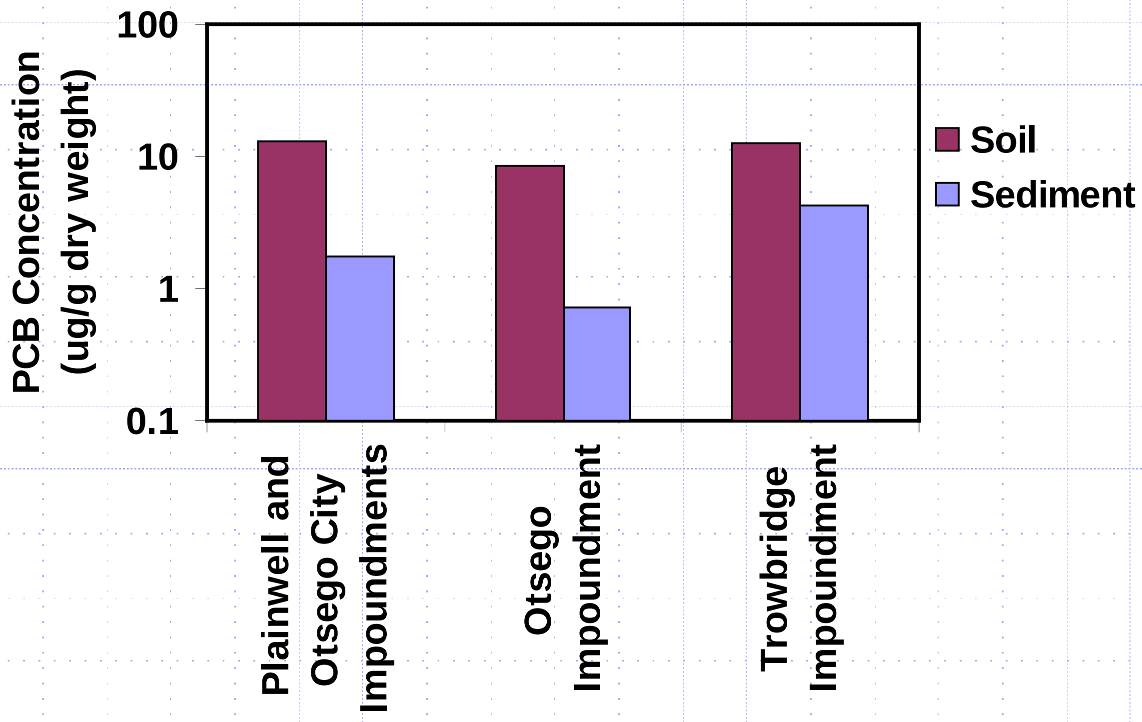
- **Analysis**
  - **Data collected 1999-2004**
  - **Duplicates averaged**
  - **Nondetects set equal to ½ DL**
  - **All surface samples with bottom depth <=6”**
  - **KRSG, EPA, MDEQ data**

PCBs in Recent Surface Sediments



PCB levels in surface sediments are very variable (4 orders of magnitude). Concentrations in the 4 impoundments are somewhat higher than upstream or downstream.

PCBs in Surface Sediments and Floodplain Soils



Average concentrations, 1999-2004

Average PCB levels in floodplain soils are greater than in surface sediments

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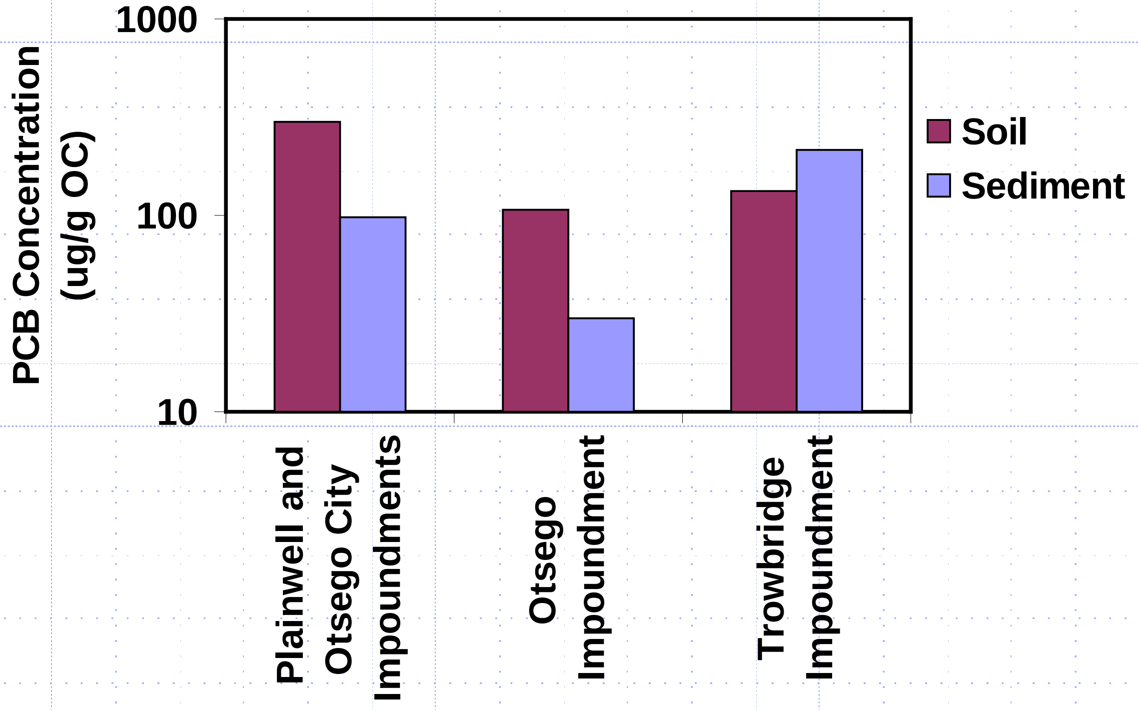
PCBs in Surface Sediments and Floodplain Soils – Carbon Basis



Average concentrations, 1999-2004

Carbon levels in floodplain soils are greater than in surface sediments, which moderates the difference in PCB levels

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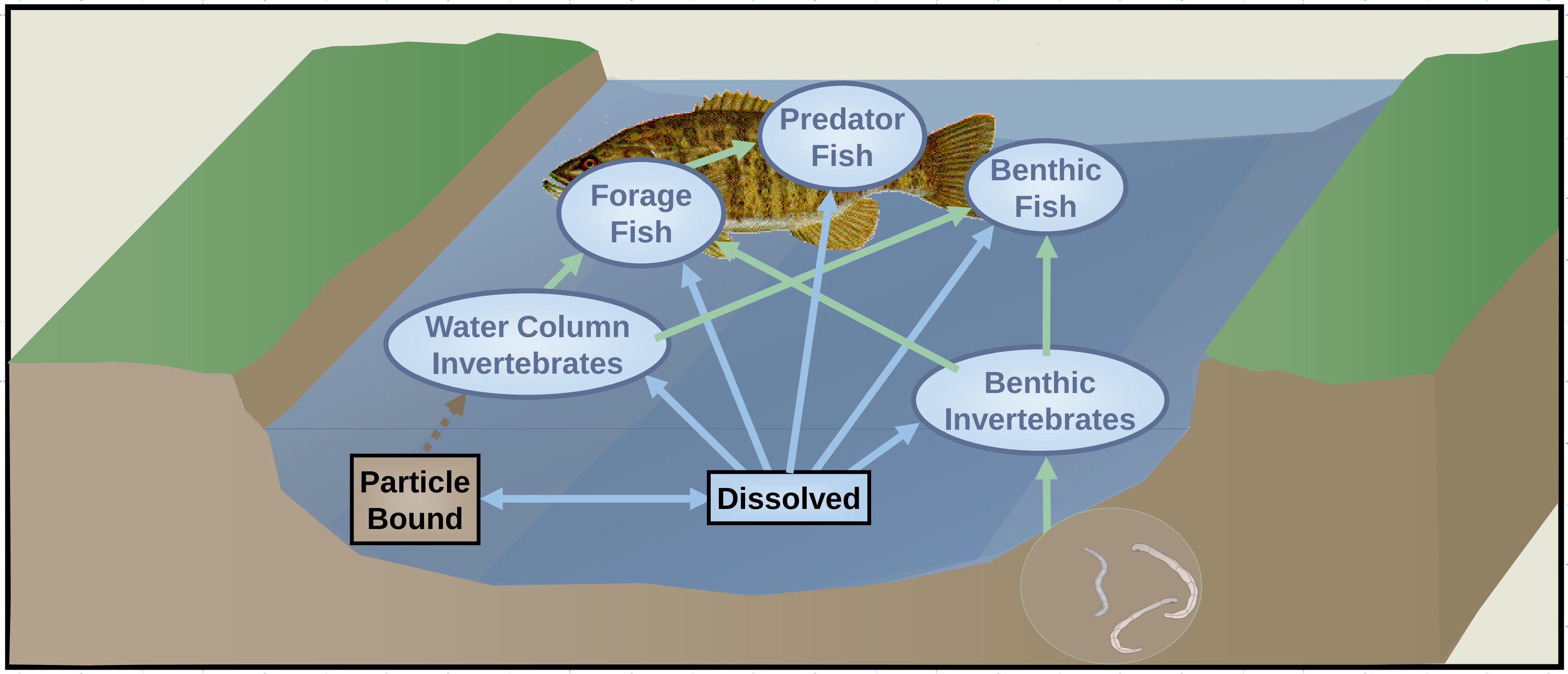
CSM Summary: Sediments

- PCB concentrations in surface sediments lower than on floodplain
  - Sediment bed incised into floodplain: below the surface contamination in the floodplain
  - Since drawdown, sediments have been diluted with less contaminated upstream and tributary solids

- Carbon levels are also lower
  - Evaluation of impacts on food web and groundwater should must account for sediment carbon content

Aquatic Food Web



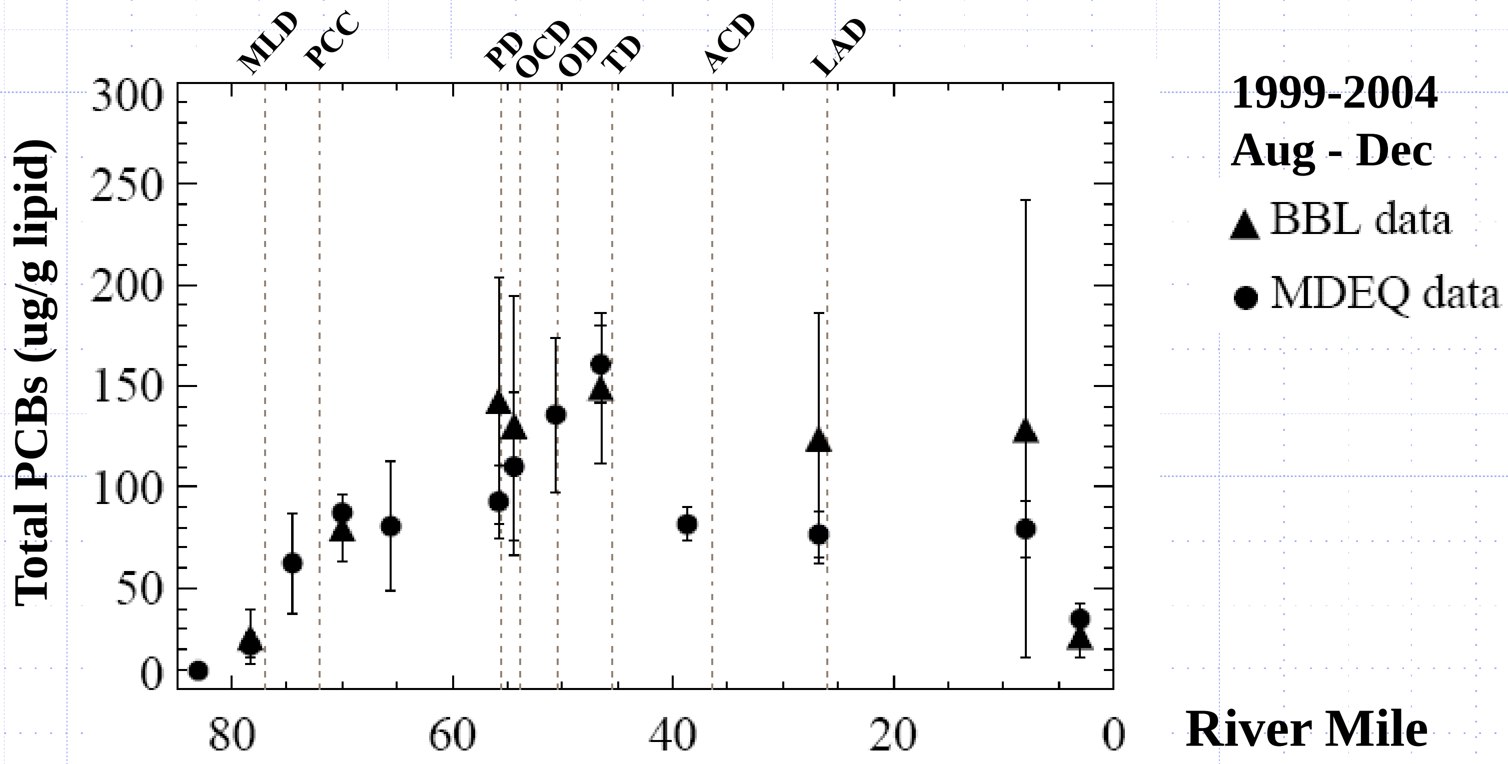
PCBs in Biota

- **Issue: How do PCB concentrations change with location in the river? Do gradients indicate likely sources?**

- **Approach**
  - **Spatial gradients in PCB concentration**
  - **Spatial gradients in bioaccumulation factors**

- **Analysis**
  - **Data collected 1999-2004**
  - **PCB concentration divided by lipid content to account for correlation**
  - **Aug – Dec data included to account for evidence of seasonal variation in PCB concentration**
  - **KRSG, MDEQ data**
  - **Smallmouth bass and carp**
  - **All sizes, males and females included**

PCBs in Smallmouth Bass



PCB concentrations in fish increase downstream to Trowbridge, and are lower downstream. This suggests distributed source(s). The pattern is similar to the pattern in water column PCBs.

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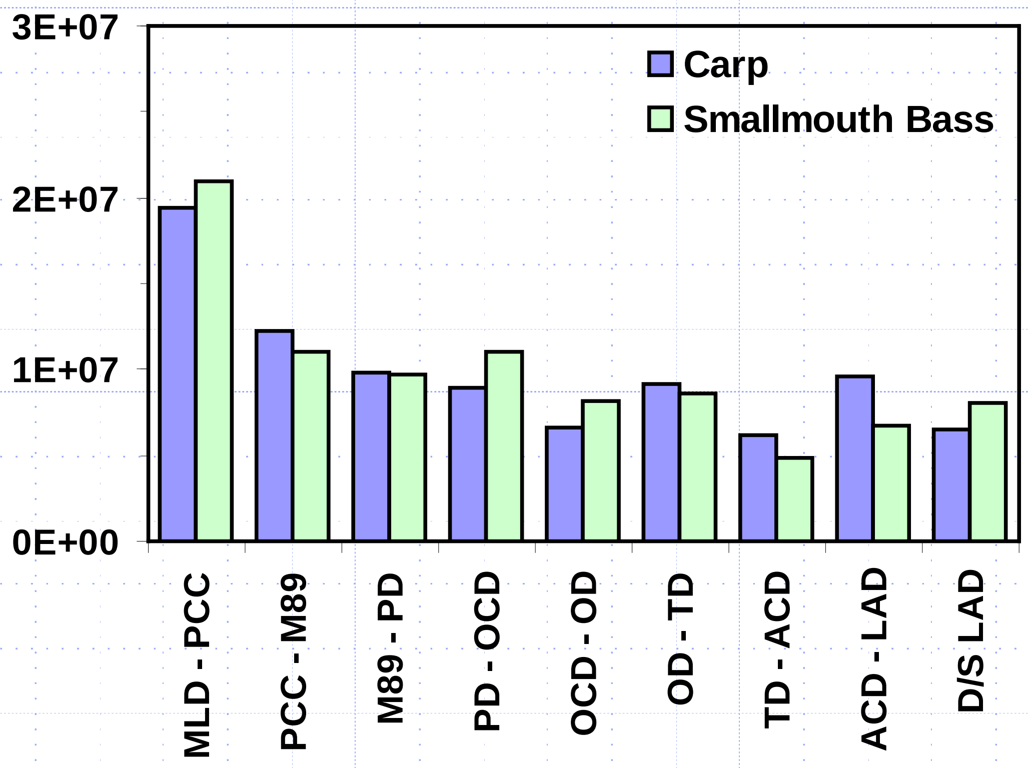
Bioaccumulation Factors

$$\text{BAF} = \frac{\text{ug/kg lipid in fish}}{\text{ug/L in water}}$$



Bioaccumulation factors decrease with distance downstream, suggesting a change in the importance of sediment & water column sources.

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CSM Summary: Fish

- PCBs in the water column are likely to be an important source to the fish
  - Spatial gradients similar
- PCBs in the sediments probably contribute to some degree
  - Sediment contribution likely decreases with distance downstream, as PCB concentrations in the water increase
- Thus, the PCBs in the fish originate from a combination of local and upstream sources

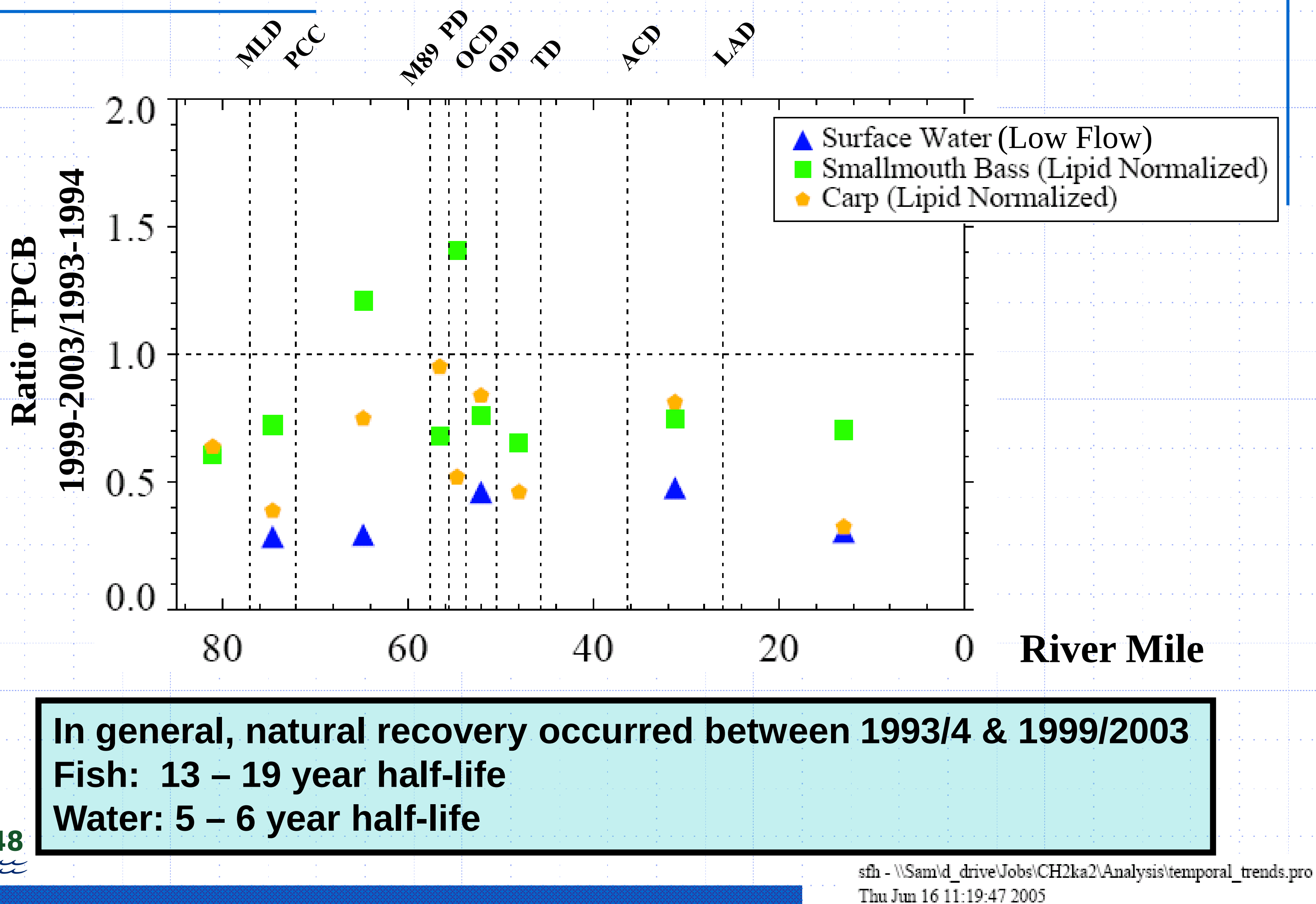
Natural Recovery

- **Issue: Have the declines in PCB concentrations observed from the 1980s to the early 1990s continued in recent years?**

- **Approach**
  - **Weight of evidence: smallmouth bass, carp & water data**
  - **Compare data collected in the early 1990s (1993/1994), with data collected more recently (1999-2003)**
    - **Compute ratio of averages: recent/older data**
  - **Evaluate reach by reach**

- **Data**
  - **Collected by KRSG and MDEQ**
  - **Fish**
    - **Lipid-normalized PCB concentrations**
    - **All sizes, seasons, males and females included**
  - **Water**
    - **Flow at Comstock <2,500 cfs**

CSM Summary: Natural Recovery



In general, natural recovery occurred between 1993/4 & 1999/2003
Fish: 13 – 19 year half-life
Water: 5 – 6 year half-life

CSM Summary: PCB Sources

- In the Kalamazoo River, no single PCB source dominates
- In the impoundments, PCBs in the water originate both from local sources and from upstream
- Sediments are a significant source to the water column
  - Low-flow: biological mechanisms, groundwater advection
  - High-flow: resuspension
- Bank erosion is likely a significant source of PCBs to the water
  - Contributes to down-river transport and to local surface sediments
- Groundwater likely provides sufficient flow to impact the transfer of PCBs from sediments to the water column
  - PCB levels in the groundwater entering the river system are not known
- Floodplain inundation appears to result in PCB load from the floodplain soils to the water
- Sources to fish probably include both local sediments and water
  - Sources to water include local sediments and transport from upstream

CSM Summary: PCB Sources

- In what proportion does each source contribute?
  - Dynamic
    - Loads depend on season
  - Spatially variable
    - Importance of upstream loadings depends on location in the river
  - Interconnected
    - Natural recovery is controlled by the interaction between bank erosion, sediment resuspension, deposition, and external loadings
  - Wide range of time scales
    - Storm loadings: hours to days
    - Fish accumulation: months to years
    - Sediment recovery: years to decades

- Quantitative source assessment requires an integrated analysis of all of the available information in a mass-balance framework